Chapter 3

Models, Scenarios, and Projections of Climate Change and Socioeconomic Change

Key Chapter Findings

- The Earth's climate is projected to change over the next century in ways that could affect food security during the next several decades. These changes, include increases in temperature, number of very hot days, precipitation intensity, length of very dry periods, and sea levels.
- The greater the increase in greenhouse-gas (GHG) emissions and concentrations, the greater the change in climate and the greater the climate-associated risks for food security.
- Societal conditions and changes are very important determinants of the ultimate impacts of climate change, because they affect overall wealth, vulnerability, willingness to allocate resources, and adaptive capacity.

The purpose of this chapter is to provide an overview of how climate and society are projected to change over the next century, to show the range of possible future conditions as currently described in the scientific literature and thus provide context for the discussion of potential effects of climate change on food security in subsequent chapters. Sections 3.1–3.3 focus on describing climate models and how they are used to project future climate change. These sections include an overview of the most recent projections of near-term (the next 20–30 years) and longer-term (the next 80–90 years) climate change, emphasizing possible changes in variables relevant to agriculture and food security. Section 3.4 describes scenarios of possible future changes in socioeconomic conditions, which are important for understanding future vulnerability and risk, as well as future adaptation and mitigation capacity.

3.1 Climate Modeling

Computer models are needed to study the highly nonlinear interactions of the Earth's climate system in a quantitative way because controlled large-scale experiments are not possible in the atmosphere itself. Climate studies rely largely on general circulation and Earth-system models, which use mathematical formulas to represent the linked, or "coupled," physical, chemical, and biological processes that drive the Earth's climate. Climate models, like weather models, generally represent the system in a three-dimensional mesh that reaches high into the atmosphere and deep into the oceans. At regularly spaced intervals, or grid points, the models use the laws of physics to calculate atmospheric and environmental variables, simulating the exchanges of mass (such as gases and aerosols/particles), momentum, and energy across the main components of the Earth system: atmosphere, oceans, land surface, and sea ice. In some models, changes in vegetation or chemical reactions between constituents are included, and a few include representation of the continental ice sheets. Because climate models cover far longer periods than weather models, their primary focus is to represent the coupled Earth system in a comprehensive way, with all the key feedback elements represented. But because of this system-level complexity, they cannot include as much detail at regional and local scales. Thus, climate projections usually focus on large regional-to-global scales rather than local scales. This approach enables researchers to simulate global climate over years, decades, centuries, or millennia. Most current-generation global models use grid points that are about 100–200 km apart, 15–30 vertical layers in the atmosphere, and up to 40 or more levels in the oceans. Scientists also use global-model results to drive finer-scale (regional) models, with grid spacing ranging from 2 to 50 km for more detailed studies of particular areas.

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Coupled climate models have been developed by many large institutions around the world. More than 40 such models contributed their output to the latest

(fifth) phase of the Coupled Model Intercomparison Project (CMIP5; Taylor et al. 2012), which provides a coordinated suite of experiments that form the basis for the results described in the 5th Assessment Report of the Intergovernmental Panel on Climate Change (IPCC; Stocker et al. 2013) and are also the basis of the climate projections included in this report. The output of Coupled Model Intercomparison Project (CMIP) experiments includes simulations of past and current conditions so that model fidelity can be evaluated through comparison to actual observations. Additionally, modeling groups perform common "control" experiments and compare results across models to help further diagnose and evaluate model performance. The full collection of models and experiments in CMIP, often including multiple experiments with the same model but different initial conditions, creates a very large database to support statistical analysis and enables better characterization of uncertainty in projections. The CMIP effort has been underway since 1995 and helps to assure that high-quality, well-documented, and comparable estimates of future climate change are available for use in research and scientific assessments, including those of the IPCC.

3.1.1 Uncertainty in Climate Models

Climate models work by representing the fundamental physical laws that govern our climate system. But they also need to approximate small-scale processes and their interaction with the larger scales that are directly simulated. There are no unique solutions to these approximations, and different models choose different approaches, all scientifically defensible, that result in different outcomes. This is the main source of model-to-model uncertainty in climate projections. For example, when the different models in CMIP5 used the same scenario of high GHG concentrations to project increases in global average temperature by 2100, the results ranged from about 3 °C to almost 6 °C (Figure 3.1), with a mean value of about 4 °C relative to average temperatures between 1986 and 2005 (Stocker et al. 2013).

It is also important to recognize that the scenario-based inputs, or "forcings" used to drive climate-model projections, such as levels of GHG emissions and concentrations, are themselves uncertain. The emissions in these scenarios depend on various assumptions about changes in global population, economic and technological development, and choices in transportation and energy use (Melillo et al. 2014). High concentrations lead to larger climate changes and lower concentrations to lower changes, but it is not possible to determine which concentration future is most likely.

Climate models differ in the way that they represent various processes (for example, cloud properties, ocean circulation, and turbulent mixing of air). As a result, different models produce slightly different projections of change, even when the models use the same scenarios. Scientists therefore often use multiple models. Section 3.3 provides mean results from all models contributing simulations to the CMIP process under a given scenario (Melillo et al. 2014).

The use of ensembles, or groups, of different climate models to perform the same simulations helps to characterize model-based uncertainty and identify the most robust patterns and, conversely, those aspects of future changes that are not yet pinned down. There is substantial agreement across models on large-scale patterns of temperature and precipitation change associated with different levels of GHG concentrations, and the driving physical processes are well understood. The choice of a high- or low-concentration scenario mainly modulates the intensity of the changes, but it does not substantially alter their geographic patterns. Intermodel variability (lack of agreement) mainly dominates in the areas around the sea-ice edge of the Arctic region for temperature-change projections and in the tropics for precipitation projections. Overall, the disagreement is significant in the magnitude of change, but not as much in the pattern or sign of the signal once it has emerged from natural variability. In general, model projections of changes in atmospheric temperatures are seen as more robust and easier to distinguish from natural variability than projections of changes in precipitation.

3.1.2 Downscaling Climate Model Results

Planning and decision processes in the agricultural sector happen at all spatial scales and generally involve a wide range of time horizons. However, global-scale modeling results at spatial resolutions of roughly 100 x 100 km, such as those discussed in this chapter, are generally seen as too coarse to be usable in regional- or local-scale analyses and management decisions. Thus, one of the most common complications when trying to integrate climate projections into these workflows is to bridge the gaps and mismatches in scales. This step of bringing the information from general circulation models to the decision level is called *downscaling*.

There is a long and deep history in downscaling climate-model output to various user needs (Benestad et al. 2008, Wilby et al. 1998). Approaches fall into two basic categories. The empirical-statistical methods exploit relationships between observed data (e.g., a weather station or grid points in a gridded observational product) and model output over a period when both are available—called the calibration period—and then estimate the higher-resolution field from the model projection, assuming a constant relationship (Benestad et al. 2008, Maurer and Hidalgo 2008, Stoner et al. 2013, Wood et al. 2002). In this category are also methods that determine the closest analog situations from the observed record, which are used to construct spatially more-coherent conditions.

The other broad downscaling approach uses dynamical models—commonly, regional climate models or regional hydrologic models—that are capable of representing important physical processes in a much more appropriate way than global models (Giorgi 1990, Hostetler et al. 2011, Mearns et al. 2013). One downside of this approach is that it often requires large (and thus expensive) computational resources. As a consequence, many downscaling analyses that use dynamical approaches cover only limited periods of time or are applied to only a limited set of general circulation models (GCMs). Additionally, "operational" regional downscaling is often still too coarse in resolution, though enhanced computational capabilities have somewhat ameliorated this problem.

Downscaling is an imperfect but often still-useful tool for bringing GCM-based climate-change predictions and projections to the appropriate scales for many uses. A number of portals are making such data available, including the Climate Change, Agriculture, and Food Security (CCAFS) project and the Nature Conservancy's Climate Wizard.

Each downscaling method has strengths and weaknesses. Users should be aware that downscaled climate information that is optimized for a particular purpose may not be ideal for different uses. For example, hydrologic and ecologic applications often require unbiased cumulative sums of precipitation over a basin or accumulated heat during the growing season while disaggregating and even reshuffling daily sequences (Maurer et al. 2002, Wood et al. 2002). Others focus specifically on the preservation of sequences, and particularly the occurrence of extremes (Yates et al. 2003, Clark et al. 2004, Bürger et al. 2012), with their specific multivariate and spatially coherent context to better represent feedback processes (Benestad et al. 2012). Similarly, direct analog-based methods (Abatzoglou and Brown 2012) also preserve the full context and are very useful to provide multivariate inputs into process models. Finally, the exploitation of dynamical methods, as is done through the use of high-resolution regional models driven by lower resolution global results, often provides the most flexible, and ultimately the only, geophysically consistent framework to study Earth system change (Kharin and Zwiers 2000, Giorgi and Mearns 2003, Racherla et al. 2012). However, such methods involve substantial computational costs and may introduce additional uncertainties through hand off of results across multiple modeling systems.

In the end, users need to be aware of the strength and weaknesses of different products, which are often designed for one particular application. Just because data are offered at spatial and temporal resolutions resembling observations does not necessarily mean that they also contain all the characteristics of real-world data. It is important to carefully evaluate data with regard to the key characteristics of the end application before application of the data.

3.2 Greenhouse-Gas (GHG) Emissions and Concentration Scenarios

To investigate human-induced climate change, researchers use projections of future GHG concentrations and other anthropogenic drivers of change, such as the emission of aerosol precursors and land-use change, as input to climate-model calculations. The most recent set of inputs developed by the scientific community, used in the CMIP5 process and many other experiments, are called representative concentration pathways (RCPs). The RCPs replace the scenarios described in the IPCC Special Report on Emissions Scenarios (SRES; Nakicenovic et al. 2000) that were used in the CMIP3 simulations (Meehl et al. 2007) that informed the IPCC 4th Assessment Report.

There are several differences between RCPs and previous sets of climate-change scenarios. RCPs are not tightly linked to a particular socioeconomic scenario; rather, each RCP is consistent with a variety of possible socioeconomic futures, including different combinations of mitigation and adaptation options. The RCPs also span a somewhat wider range of concentration pathways and outcomes than the SRES scenarios, particularly on the low end, because the RCPs include emissions-mitigation scenarios, while the SRES scenarios do not. Care must be taken when comparing RCP-driven results with those driven by previous scenarios, as there are significant differences in the underlying emissions and concentrations in some instances.

There are four different RCPs used in the CMIP5, each of which represents a different pathway of potential changes in GHG concentration levels over the 21st century and each of which is named for the approximate radiative forcing (a measure of the additional greenhouse effect imposed by the changes in gases, aerosols, and land use) it will produce in 2100 in terms of watts-per-square-meter change relative to preindustrial conditions. The output of climate-model simulations driven by each RCP is a projection of the rate and magnitude of climate change over the 21st century. This information can be combined with socioeconomic and biological information and models to investigate the potential effects of climate change.

For the purposes of this report, we concentrate our description on the differences between a low-emissions case and a high-emissions case. This approach spans a broad range of possible future climate conditions and enables us to address the potential effects of actions to reduce GHG emissions versus allowing continued rapid emissions growth. RCP 2.6 is a low-emissions scenario that assumes extensive mitigation efforts to reduce emissions, resulting in a CO_2 concentration of about 421 ppm by 2100 (van Vuuren et al. 2011). RCP 8.5 is a high-emissions scenario that produces a CO_2 concentration of 936 ppm by the end of the century (Riahi et al. 2011). In some instances, we also discuss results from studies that used other low- and high-emissions scenarios, such as SRES, or studies that used more intermediate scenarios, such as RCP 4.5 and RCP 6.0. For reference, current CO_2 concentrations in the atmosphere are around 400 ppm, whereas preindustrial levels were approximately 280 ppm.

3.3 Climate Projections

The CMIP5 process used the four RCPs described previously as drivers for simulations of the future evolution of Earth's climate (Moss et al. 2010, van Vuuren et al. 2011). This large ensemble of simulations delivers a wealth of information in terms of primary variables (temperature, precipitation, etc.) and derived indices (e.g., frost days, growing-season length, and precipitation intensity). Extensive documentation of many aspects of historical, short-term (next few decades), and long-term (throughout the century and beyond) climate trajectories is available in Chapters 10, 11, and 12 of the IPCC 5th Assessment Report. Chapter 9 of the same report includes a discussion of model evaluations (Stocker et al. 2013).

The new set of climate projections confirm and extend the findings of previous studies described in the scientific literature and earlier IPCC reports such as the 4th Assessment Report (Solomon et al. 2007). As expected, the range of results is somewhat wider because of the wider range of forcing levels spanned by the RCPs compared to previous emissions scenarios. The geographical patterns and magnitude of change (conditional on the scenario used) are consistent with previous work.

If GHG emissions and concentrations continue to increase rapidly throughout the 21st century (as represented in RCP 8.5), global average temperature is projected to increase by about 2 °C by 2050 and by about 4 °C by 2100 (Stocker et al. 2013), relative to global average temperature during the period from 1986–2005. Global average sea level is projected to rise by about 0.22–0.38 m by mid-century (2046–2064) and 0.45–0.82 m by late century (2081–2100) relative to 1986–2005 (Stocker et al. 2013).

If aggressive mitigation actions are taken to slow the increase of GHG emissions and concentrations, global average temperature is projected to increase by about 1 °C by 2050 and remain at about that level through 2100 (Stocker et al. 2013), relative to the 1986–2005 average. The likely range described here is slightly less than the 0.3–1.2 m projected by the Third U.S. National Climate Assessment for late century (Melillo et al. 2014).

Figure 3.1 shows global average temperature changes resulting from all four RCPs out to 2100, with respect to a baseline taken as 1986–2005. RCP 2.6 assumes strong mitigation actions, with GHG concentrations peaking at about 450 ppm in 2040 followed by a slight decline. It is the only scenario under which trajectories of global average temperature are not increasing steadily over the course of this century. The other three RCPs produce steadily increasing trajectories of GHG concentrations.

Projected changes from today's global average temperature by 2100 range from an ensemble mean value of about 1 °C for RCP 2.6 to an ensemble mean value of about 4 °C for the highest scenario, RCP 8.5. A 2 °C warming threshold with respect to preindustrial levels would not likely be exceeded under an RCP 2.6 scenario (Stocker et al. 2013). Under RCP 4.5, it is more likely than not to be exceeded, and under RCPs 6.0 and 8.5, it is likely to be exceeded (Stocker et al. 2013).

Geographical patterns of change have proven stable across at least the last three generations of assessments and models (Tebaldi and Arblaster 2014). Maps of annual average temperature change derived from the CMIP5 multimodel ensemble for RCP 2.6 and RCP 8.5 are shown in Figure 3.2.

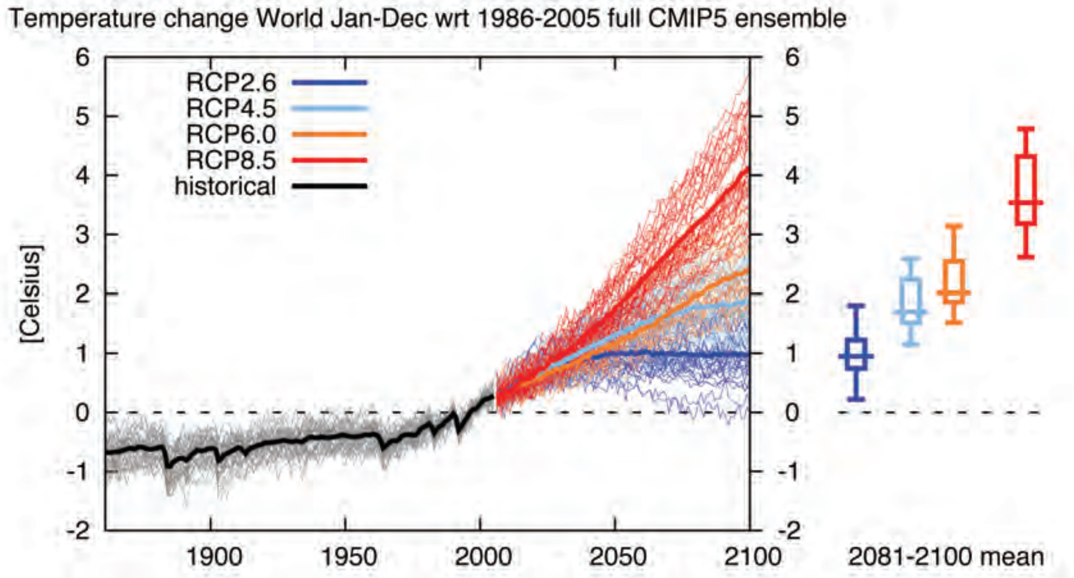

Figure 3.1 Global average temperature change relative to 1986–2005 baseline. *Time series of surface temperature under historical forcings (gray) and future RCPs 2.6 (low-emissions scenario, in blue), 4.5 (aqua), 6.0 (orange), and 8.5 (high-emissions scenario, in red) are shown out to 2100. Thin lines show individual model trajectories; thick lines show the multimodel ensemble mean. Boxplots in margin show the distribution (mean, interquartile range, and 90% range) derived from the model ensemble for the average changes over the 20-year period at the end of the century. Source: This figure was produced using CMIP5 model output through the web application "Climate Explorer," available at http://climexp.knmi.nl/.*

Well-known features of temperature change can be seen in Figure 3.2: high latitudes warm more than low latitudes, continents more than oceans, and the Northern Hemisphere more than the Southern. The RCP 2.6 low-emissions scenario results in warming of about 1–2 °C by mid-century for much of North and South America, Europe, Africa, Australia, and Asia, and this level of warming persists through the end of the century. Warming in some northern areas exceeds 2 °C. The RCP 8.5 high-emissions scenario results in warming of 2–3 °C by mid-century for North and South America, Europe, Africa, Australia, and Asia. By late century, this scenario results in 4–5 °C warming in these same areas, with some high-latitude northern regions experiencing warming of 7 °C or more. The North Atlantic experiences less warming than surrounding areas due to the Atlantic Meridional Overturning Circulation in the ocean slowing down because of warmer temperatures and increased freshwater inputs. Similarly, changes in the southern oceans also result in somewhat reduced warming in some locations due to better and deeper mixing of the ocean layers there.

Global precipitation is projected to increase, due to the ability of warmer air to hold more moisture (made available by enhanced evaporation from the oceans), but change may not be distributed uniformly in time or space (Figure 3.3). Increased precipitation is projected for many areas, but longer periods with little or no precipitation are projected for several regions that are already dry.

Precipitation is also projected to become more intense, but the distribution of precipitation intensity over the surface of the Earth is again not projected to be uniform (Figure 3.4). Mid-latitude land regions and wet tropical regions are very likely to see more-intense and more-frequent precipitation events by the end of the century (Stocker et al. 2013). In general, the pattern of wet areas becoming wetter and semiarid regions becoming drier seen in most earlier generations of climate simulations is confirmed by CMIP5 simulations for both low- and high-emissions scenarios. Some of the most prominent and robust features of future changes in precipitation are increases at high latitudes and the equatorial region of the Pacific Ocean and decreases in the subtropics, with a particularly strong negative signal over the Mediterranean basin and Western Australia.

Larger temperature increases over land than over ocean surfaces mean that most regions are projected to experience decreases in relative humidity as temperatures increase. The primary exceptions to this pattern are in regions of tropical Africa, India, and South America, where increases in relative humidity are anticipated (O'Gorman and Muller 2010).

These broad regional patterns of change in temperature and precipitation are common across all scenarios and are driven for the most part by increasing long-lived, well-mixed GHG. They are also common across time (for example, they can be seen in average changes around the middle of the

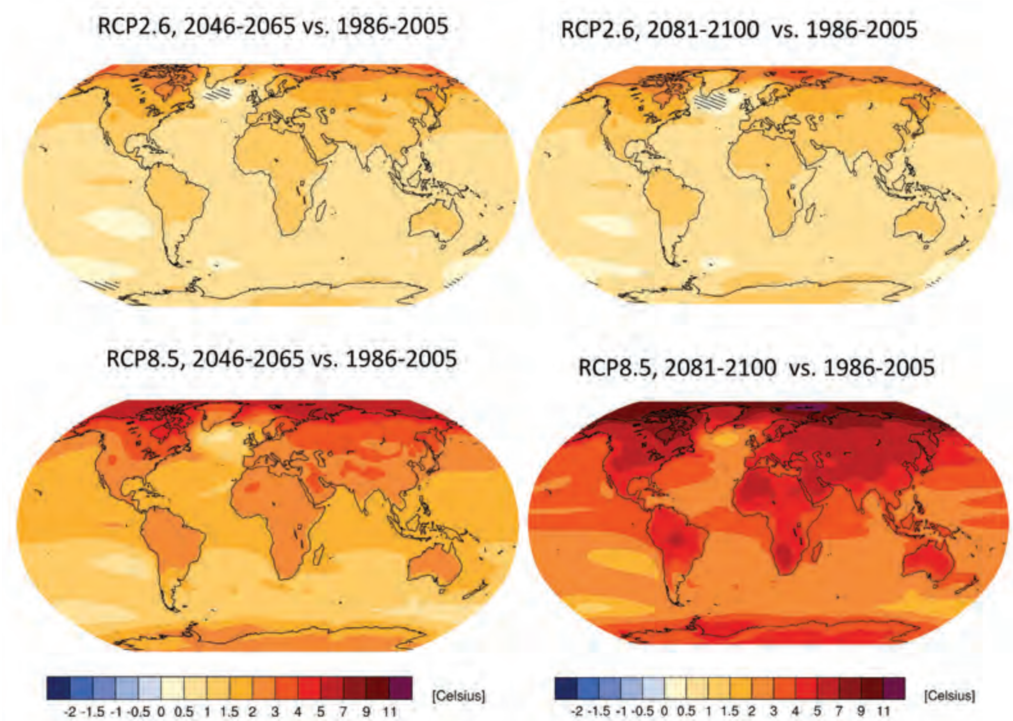

Figure 3.2 Projected changes in global surface temperature. *Mid (left) and late (right) 21st-century changes are compared with the period 1986–2005 for low-emissions (RCP 2.6, top) and high-emissions (RCP 8.5, bottom) scenarios. Multimodel ensemble-mean changes are shown where gray dashes indicate areas where changes are small (less than one standard deviation) compared to natural variability. The differences between scenarios get larger as time progresses. Source: This figure was produced using CMIP5 model output through the web application "Climate Explorer," available at http://climexp.knmi.nl/.*

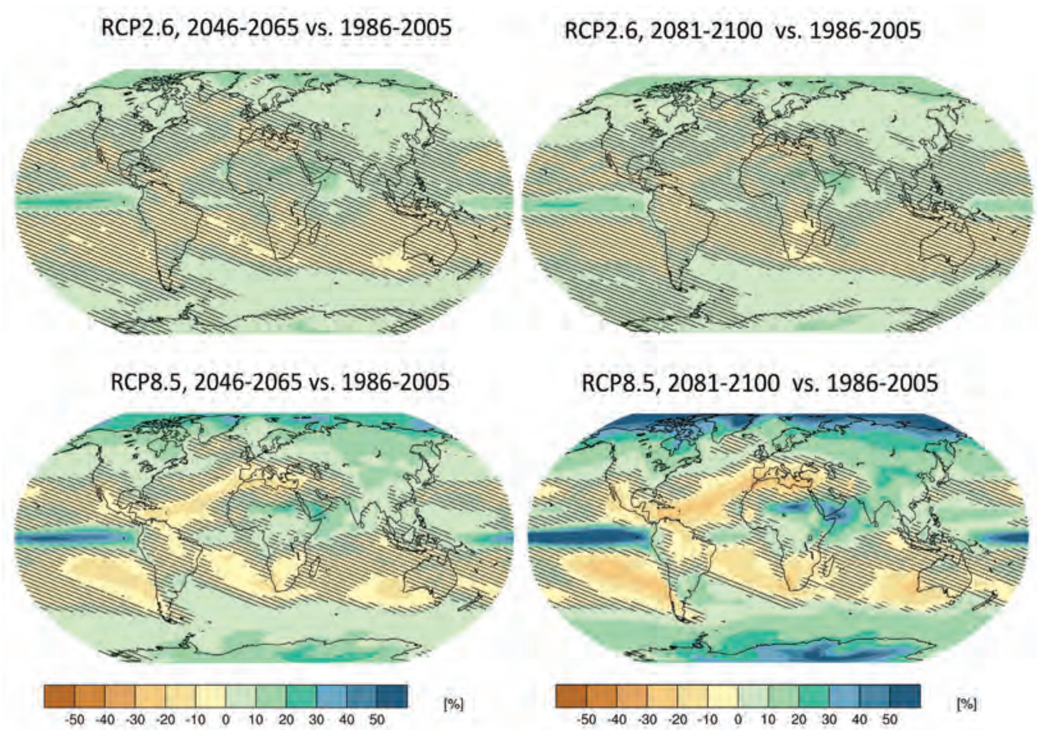

Figure 3.3 Projected changes in global precipitation. *Mid (left) and late (right) 21st-century changes are compared with the period 1986–2005 for low-emissions (RCP 2.6, top) and high-emissions (RCP 8.5, bottom) scenarios. Multimodel ensemble-mean changes are shown where gray dashes indicate areas where changes are small (less than one standard deviation) compared to natural variability. The general pattern is of wet regions becoming wetter and dry regions drier. Source: This figure was produced using CMIP5 model output through the web application "Climate Explorer," available at http://climexp.knmi.nl/.*

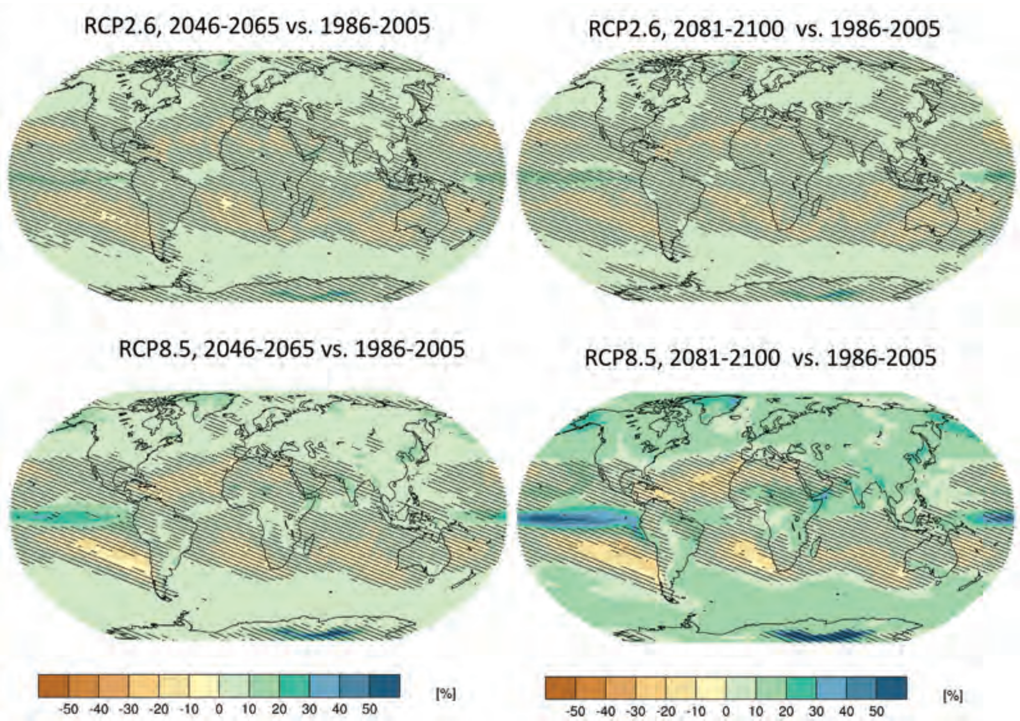

Figure 3.4 Projected changes in precipitation intensity. *Mid (left) and late (right) 21st-century changes are compared to the 1986–2005 baseline under the low-emissions (RCP 2.6, top) and high-emissions (RCP 8.5, bottom) scenarios. Multimodel ensemble-mean changes are shown where gray dashes indicate areas where changes are small (less than one standard deviation) compared to natural variability. Precipitation intensity is defined as the total amount of annual precipitation divided by the number of wet days. Source: This figure was produced using CMIP5 model output through the web application "Climate Explorer," available at http://climexp.knmi.nl/.*

century as well as those at the end of the century) and, in first approximation, across models. The regions of largest discrepancies among models are the very high latitudes for temperature and, conversely, the low latitudes for precipitation.

Soil moisture is another important variable for agriculture that integrates the history of temperature and precipitation to some extent. Projected changes in soil moisture are shown in Figure 3.5. There are notable differences between changes under high versus low scenarios of GHG emissions and concentrations. Results for RCP 2.6 show some drying in high-latitude regions and central South America, with increased moisture in many other areas, while RCP 8.5 results in much more extensive drying in mid-latitude regions as well as high latitudes. This is seen in both the near-term and long-term projections, with the most extensive reductions found in the high-emissions results for the end of the century. This is a reflection of the fact that temperature plays an important role in depleting the soil of moisture through evaporation, and warming is significantly higher under the high-emissions scenario by the end of the century.

Another important agricultural quantity that can be derived from climate-model simulations is length of the growing season. Figure 3.6 shows projected changes in an index that adopts a simplified and uniform definition, where growing season length is represented by the number of consecutive days during the year with an average temperature above 5 °C. This index does not capture changes in tropical and subtropical areas that do not experience temperatures below 5 °C, where exceedance of physiological thresholds with higher temperatures can reduce growing season length. The RCP 2.6 low-emissions scenario results in growing seasons that are up to about 10% longer than currently throughout much of the mid-latitudes in the Northern Hemisphere by mid-century, without much further change by the end of the century. Some higher latitude areas of the Northern Hemisphere could see increases of 20%–30% and very high latitudes increases of 80%–100% by mid-century. For the RCP 8.5 high-emissions scenario, many of the northern mid-latitude areas see increases of 20%–30% by mid-century, with a more extensive area at very high latitudes increasing by 70%–100%.

The index displayed in Figure 3.6 does not capture change in tropical and subtropical areas, which are expected to experience shorter growing seasons due to lack of sufficient moisture and temperature increases that exceed physiological tolerances for

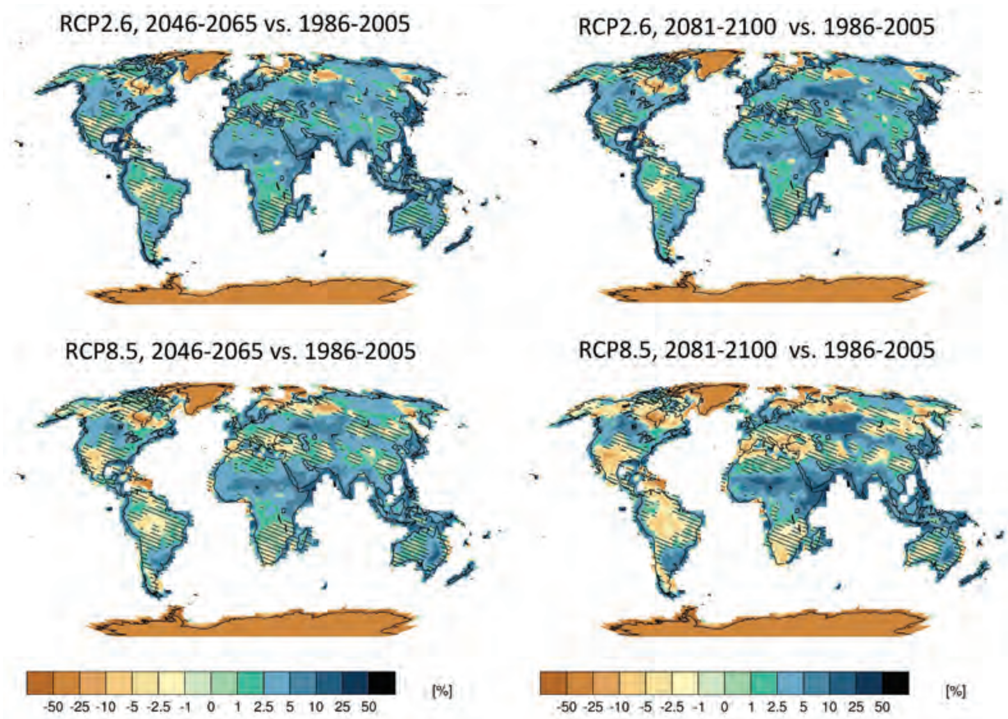

Figure 3.5 Projected changes in soil moisture. *Mid (left) and late (right) 21st-century changes are compared to the 1986–2005 baseline under the low-emissions (RCP 2.6, top) and high-emissions (RCP 8.5, bottom) scenarios. Multimodel ensemble-mean changes are shown where gray dashes indicate areas where changes are small (less than one standard deviation) compared to natural variability. Drying is much more pronounced in the higher emissions scenarios, particularly toward the end of the century. Source: This figure was produced using CMIP5 model output through the web application "Climate Explorer," available at http://climexp.knmi.nl/.*

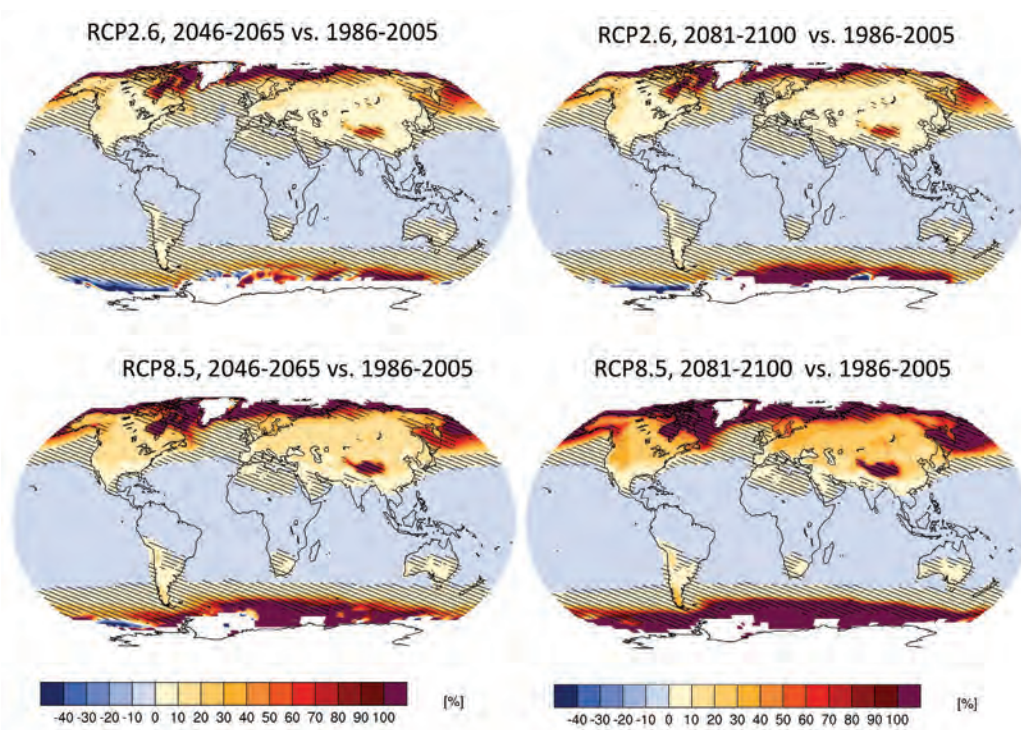

Figure 3.6 Projected changes in growing season length. *Mid (left) and late (right) 21st-century changes are compared to the 1986–2005 baseline under the low-emissions (RCP 2.6, top) and high-emissions (RCP 8.5, bottom) scenarios. Multimodel ensemble-mean changes are shown where gray dashes indicate areas where changes are small (less than one standard deviation) compared to natural variability. Source: This figure was produced using CMIP5 model output through the web application "Climate Explorer," available at http://climexp.knmi.nl/.*

many crops. In semiarid regions of the tropics, the length of the growing season is not determined by the number of days with temperatures greater than 5 °C, but by the balance between water supply (precipitation) and atmospheric water demand (potential evapotranspiration). In many areas, the latter will increase with increasing air temperatures. In some regions, these effects are expected to lead to substantial reductions in the length of the viable growing seasons by mid-century (Thornton et al. 2011, Cook and Vizy 2012).

Changes in average climate conditions are important, but agricultural production and other food-system elements are also affected by changes in extreme conditions. Figures 3.7 through 3.9 show changes in the tails (i.e., extremes) of the distribution of values derived from daily output of temperature or precipitation (Sillmann et al. 2013). The Frost Days index (Figure 3.7) counts the number of days in the year with minimum temperatures below freezing. The Consecutive Dry Days index (Figure 3.8) measures the longest stretch of days without agriculturally meaningful (>0.1 mm/day) precipitation every year. Finally, Figure 3.9 shows projected changes in the number of very hot days, defined as days with maximum temperatures in the upper 10% of observed daily highs in 1986–2005.

The maps of changes in frost days show a uniform decrease of such cold days all over the Earth's surface, with the regions experiencing the greatest warming (some areas of the high latitudes of the Northern Hemisphere) also showing the largest changes in this measure. The lowest decreases are seen in the near-term, low-emissions scenario and the greatest decreases in the long-term, high-emissions scenario.

The story told by changes in consecutive dry days (Figure 3.8) is consistent with precipitation changes, with large areas of the subtropics seeing significant lengthening of dry spells, while many of the high-latitude regions, where precipitation is expected to increase, see significant shortening of dry spells. The largest drying is seen in the long-term, high-emissions scenario, with many mid-latitude and tropical areas experiencing 30%–50% increases.

Looking at very hot days (Figure 3.9) in the low-emissions scenario (RCP 2.6), shows increases of 10%–20% in such days across large areas of

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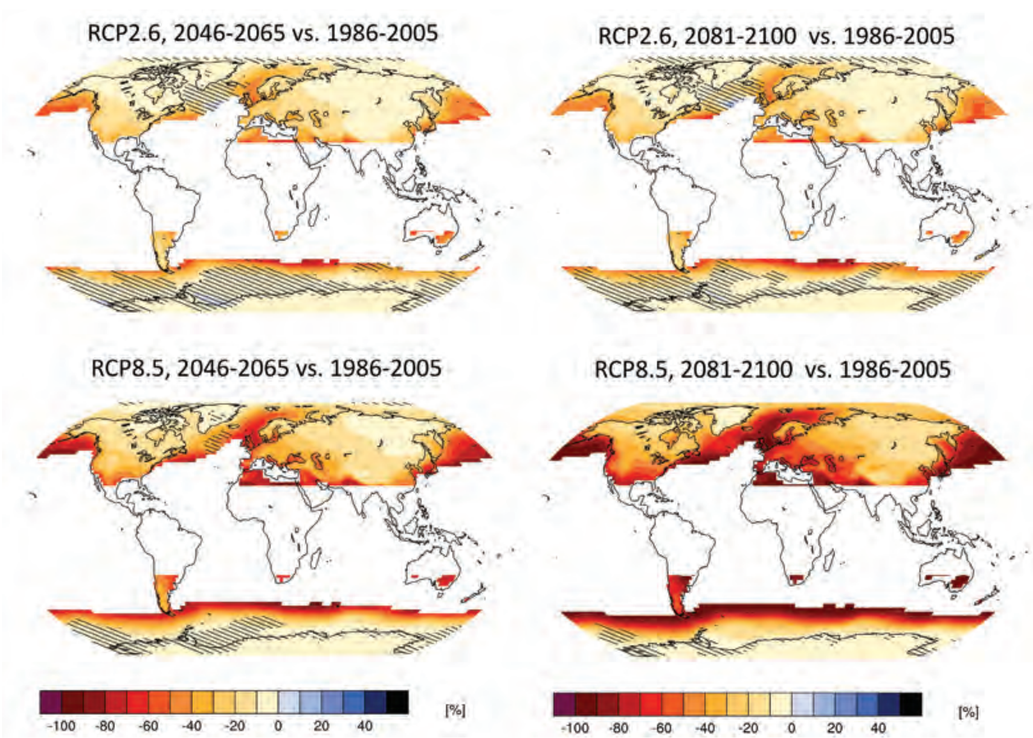

Figure 3.7 Projected changes in frost days. *Mid (left) and late (right) 21st-century changes are compared to the 1986–2005 baseline under the low-emissions (RCP 2.6, top) and high-emissions (RCP 8.5, bottom) scenarios. Multimodel ensemble-mean changes are shown where gray dashes indicate areas where changes are small (less than one standard deviation) compared to natural variability. Frost days are defined as the number of days during a calendar year with the minimum temperature falling below 0 °C. Source: This figure was produced using CMIP5 model output through the web application "Climate Explorer," available at http://climexp.knmi.nl/*

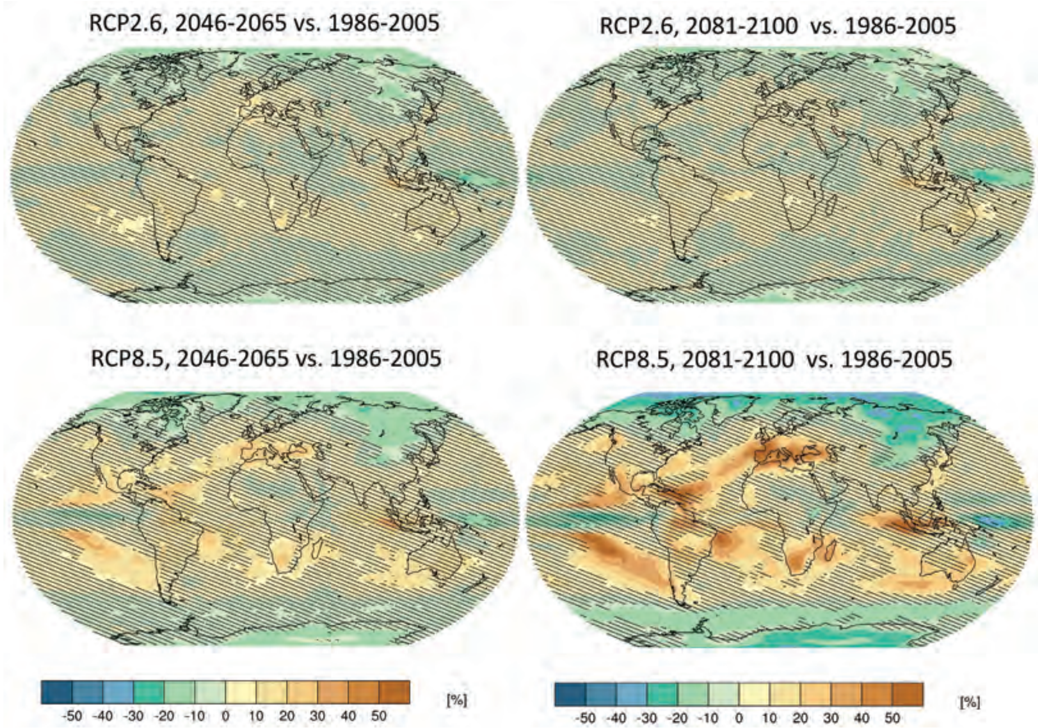

Figure 3.8 Projected changes in annual maximum number of consecutive dry days. *Mid (left) and late (right) 21st-century changes are compared to the 1986–2005 baseline under the low-emissions (RCP 2.6, top) and high-emissions (RCP 8.5, bottom) scenarios. Multimodel ensemble-mean changes are shown where gray dashes indicate areas where changes are small (less than one standard deviation) compared to natural variability. Source: This figure was produced using CMIP5 model output through the web application "Climate Explorer," available at http://climexp.knmi.nl/*

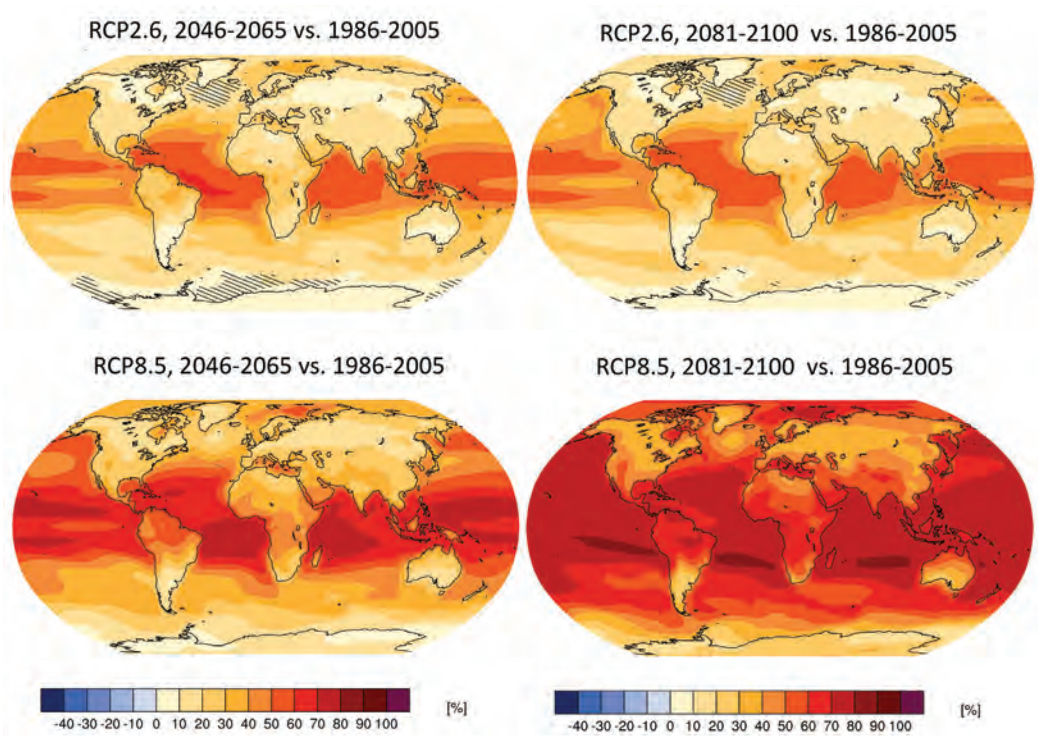

Figure 3.9 Projected changes in annual number of very hot days. *Mid (left) and late (right) 21st-century changes are compared to the 1986–2005 baseline under the low-emissions (RCP 2.6, top) and high-emissions (RCP 8.5, bottom) scenarios. Multimodel ensemble-mean changes are shown where gray dashes indicate areas where changes are small (less than one standard deviation) compared to natural variability. Very hot days are when maximum daily temperatures are above the 90th percentile of current climatology. Source: This figure was produced using CMIP5 model output through the web application "Climate Explorer," available at http://climexp.knmi.nl/.*

continental interiors in the mid-latitudes and tropics, with smaller areas seeing increases of 30%–40%. This change persists in the long term, with late-century conditions quite similar to those seen in mid-century. The high-emissions scenario results in a greater number of very hot days. In the near term, large areas of the mid-latitude continental interiors are projected to see increases of 30%–40%, and some parts of South America and Africa may see increases of over 50%. In contrast to the low-emissions scenario, changes continue to occur and grow in magnitude. These increases may reduce the length of the effective growing season in some places in Africa, for example, by the middle of the 21st century (Cook and Vizy 2012). By the end of the 21st century, large parts of South America and Africa are projected to see increases of 60%–70% in the number of very hot days compared with today.

By mid-century, many regions are likely to experience temperatures that are outside historically observed natural variability, but changes in precipitation are not as clearly distinct. By late century, both temperature and precipitation are more unambiguously affected by increased atmospheric GHG concentrations. For the low-emissions scenario, the changes from mid-century to late century are not very large, reflecting the fact that this scenario stabilizes concentrations and thus the associated climate response. The continued increase in GHG concentrations under the high-emissions scenario results in greater change in the near term, with continued change from mid- to late century.

3.4 Socioeconomic Change

One of the challenges in assessing the potential future effects of climate change is that human systems and ecosystems are changing at the same time as climate changes are occurring. Some of these changes are themselves affected or driven by climate change while others are largely independent but still relevant to the overall capacity of society to adapt to or mitigate climate change. In addition, because many socioeconomic changes will not be tightly coupled with climate change, there is a range of possible climate futures associated with any given socioeconomic future and vice versa.

The rate and magnitude of recent technological and socioeconomic changes are very large. Global population increased from about 2.5 billion in 1950 to over 7 billion today. Global GDP changed from about USD 5.3 trillion to about USD 77.6 trillion over this same period. This rapid evolution must be considered in assessment of potential future effects

of climate change. Examining the way that different climate conditions would affect today's world can offer insights into some aspects of vulnerability but is unlikely to provide an accurate picture of future risks. In order to construct meaningful assessments of the potential future impacts of climate change, as well as possibilities for mitigation and adaptation, projections of future climate change need to be combined with projections of future biophysical and socioeconomic conditions, including demographic, economic, technological, social, and governance outcomes and the couplings and feedbacks between human and ecological systems (Ostrom 2009).

A wide variety of projections and scenarios of socioeconomic change have been created over the last several decades to support the assessment and analysis of environmental change, including those developed by the Millennium Ecosystem Assessment (2005), the IPCC Special Report on Emissions Scenarios (SRES; Nakicenovic et al. 2000), and the United Nations Environment Programme (UNEP 2007). All have been and continue to be widely used in climate impact studies–some results based on SRES scenarios are also considered in this document.

3.4.1 Shared Socioeconomic Pathways

More recently, the scientific community has developed new descriptions of socioeconomic

futures called Shared Socioeconomic Pathways (SSPs) to facilitate climate-change research and assessment (O'Neill et al. 2014 and 2015, Ebi et al. 2014, Dellink et al. 2015). The SSPs are intended to describe future socioeconomic changes that could occur at the same time that climate is changing and that could affect the ability of societies to respond. Capturing the range of uncertainty in future societal conditions is an enormous task, given the myriad ways and rates at which societies may develop. In response to this difficulty, the SSPs are designed to span a wide but plausible range of societal conditions in two particular dimensions: (1) challenges to mitigation and (2) challenges to adaptation (O'Neill et al. 2014). These challenges are defined by a combination of elements, such as population growth, urbanization, education levels, income growth, technological progress, effectiveness of institutions, and so on (Rothman et al. 2013, Schweizer and O'Neill 2014).

Five SSPs have been developed. SSP1 assumes low challenges to mitigation and adaptation; SSP2 assumes medium challenges to both; SSP3 assumes high challenges to both; SSP4 assumes that adaptation challenges dominate; and SSP5 assumes that mitigation challenges dominate. Each SSP consists of a qualitative narrative, summarized below, describing general trends in the various elements of societal conditions and the logic for how and why these trends unfold together over time. In addition, each SSP will include quantitative projections—global and country-by-country—of key elements: population projections by age, sex, and education level; urbanization; and changes in GDP. Some of these have been published or submitted for publication; others are still under development. None is considered more or less likely than another.

SSP1: Low challenges to mitigation and adaptation. The world shifts gradually, but pervasively, toward a more sustainable path, emphasizing more-inclusive development that respects perceived environmental boundaries. Management of global environmental issues slowly improves, facilitated by increasingly effective and persistent cooperation and collaboration at local, national, and international levels across governments, the private sector, and civil society. Educational and health investments accelerate the demographic transition, leading to a relatively low population growth. Beginning with current high-income countries, the emphasis on economic growth shifts toward a broader emphasis on human well-being. Somewhat slower long-term economic growth is accepted and inequality is reduced across and within countries. Investment in environmental technology and changes in tax structures lead to improved resource efficiency, reducing overall energy and resource use and improving environmental conditions over the longer term. Increased investment, financial incentives, and changing perceptions make renewable energy more attractive.

SSP2: Moderate challenges to mitigation and adaptation. The world follows historical social, economic, and technological trends. Development and income growth proceed unevenly, but most economies are politically stable. Globally connected markets function imperfectly. Global and national institutions make slow progress improving living conditions and access to education, safe water, and health care. Technological development proceeds but without fundamental breakthroughs. Environmental systems mainly degrade, although there are some improvements. Overall intensity of resource and energy use declines. Fossil fuel dependency decreases slowly, but there is no reluctance to use unconventional fossil resources. Global population growth is moderate and levels off in the second half of the century, but the transition to low fertility rates in low-income countries is not accelerated. Persistent income inequality, continued societal stratification, and limited social cohesion result in continued vulnerability to societal and environmental changes and constrain sustainable development.

SSP3: High challenges to mitigation and adaptation. Concerns about regional identity, regional conflicts, competitiveness, and security, coupled with relatively weak global institutions, push countries to increase their focus on domestic and/or regional rather than global issues. Barriers to trade grow, particularly in the energy and agricultural markets. Countries focus on energy and food-security goals within their own regions and in some regions move toward more authoritarian government with highly regulated economies. Investment in education and technological development declines, economic development is slow, consumption is material-intensive, and inequalities persist or worsen over time, especially in developing countries. Many countries struggle to provide access to safe water, improved sanitation, and health care for disadvantaged populations. The combination of impeded development and limited environmental concern results in environmental degradation and poor progress toward sustainability. Population growth is low in developed countries and high in developing countries.

SSP4: Low challenges to mitigation, high challenges to adaptation. Highly unequal investment in human capital, and increasing disparities in economic opportunities and political power, lead to increasing inequalities and stratification across and within countries. Over time, a gap widens between an internationally connected, well-educated society that contributes to and benefits from the global economy and a fragmented collection of lower-income, poorly educated societies that work in a labor-intensive, low-tech economy. Vulnerable groups have little representation in national and global institutions. Economic growth is moderate in developed and middle-income countries, while low-income countries struggle to provide adequate access to water, sanitation, and health care for the poor. Social cohesion degrades, and conflict and unrest are increasingly common. Technology development is high in the high-tech economy and sectors. Uncertainty in fossil fuel markets leads to underinvestment in new resources in many regions. Oil and gas prices rise, volatility increases, and energy companies invest in both low-carbon energy sources and carbon-intensive fuels such as coal and unconventional oil. Environmental policies focus on local issues around middle- and high-income areas.

SSP5: High challenges to mitigation, low challenges to adaptation. The world relies on competitive markets, innovation, and participatory societies (i.e., societies with extensive citizen involvement in decision making), to produce strong global economic growth, rapid technological progress, and development of human capital. Global markets are increasingly integrated and focused on maintaining competition and removing institutional barriers to the participation of disadvantaged population groups. Large investments in health, education, and institutions enhance human and social capital. Increased exploitation of abundant fossil-fuel resources results in adoption of resource- and energy-intensive lifestyles around the world. There is faith in the ability to effectively manage social and ecological systems, including by geo-engineering if necessary. Local environmental impacts are addressed effectively by technological solutions, but there is relatively little effort to avoid potential global environmental impacts due to a perceived trade-off with economic development. Global population peaks and declines in the 21st century. Though fertility declines rapidly in developing countries, fertility levels in high-income countries are relatively high (at or above replacement level) due to optimistic economic outlooks.

Taken together, the set of RCPs and SSPs provides a basis for the scientific community to conduct systematic and comparable analyses of future vulnerability, risks, and effects of climate change in

the context of other environmental and socioeconomic changes. Most of the integrated modeling results examined in this assessment used combinations of SSP1, SSP2, and SSP3 with RCP 2.6 and RCP 8.5, although some results based on the SRES scenarios are also included. In some cases, SSPs are also used as a frame for qualitative assessment of likely future risks to food security, as they occur alongside other environmental and socioeconomic changes.

3.5 Conclusions

The projection of future climate and socioeconomic change is complicated by multiple interacting sources of uncertainty that vary over time. Climate projections are based on different estimates of future GHG emissions and concentrations. These emission- and concentration-scenario inputs, and the projections based on them, are more certain in the near term than the long because of the considerable inertia in energy infrastructure. However, near-term climate projections also include natural variability that is not always possible to distinguish from human-induced change in near-term results.

Over the longer term, socioeconomic futures and thus emission- and concentration-scenario inputs to projections are much more uncertain. The literature does not provide definitive answers about the relative likelihood of high versus low emissions and concentrations over the course of the next century, but there are increasingly clear differences between the climate outcomes from high-concentration and low-concentration scenarios. In low-concentration scenarios, natural variability still plays a significant role next to projected changes. In high-concentration scenarios, it is much easier to distinguish human-induced change from natural variability.

The Earth's climate is projected to continue changing over the coming decades and this century.

The current best practices for projecting climate change and its effects thus tend more toward identifying and investigating a range of plausible trajectories for future emissions and concentrations (e.g., representative concentration pathways) and a plausible range of possible societal conditions that affect vulnerability and adaptive capacity (e.g., shared socioeconomic pathways) rather than trying to determine a single, most-likely outcome. Using plausible future emissions to drive climate projections and plausible socioeconomic futures to assess vulnerability and response capabilities has enabled scientists to make contingent projections of future physical conditions and to identify some of the potential impacts of and adaptations to changing climate.

In summary, the Earth's climate is projected to continue changing over the coming decades and this century. Some degree of change will occur in response to past emissions even if aggressive action is taken to limit GHG increases in the future. Many projected changes are directly relevant to agriculture and food security, including increased temperatures, increased incidence of very hot days, decreased incidence of very cold days, increased precipitation, increased precipitation intensity, longer dry periods, decreased soil moisture in many regions, and rising sea levels.

The greater the increase in GHG concentrations, the greater the climate change and the greater the climate risks that will be experienced over the next 100 years and beyond; the lesser the increase, the lesser the change and the lesser the risks. It remains difficult to separate human-induced change from natural variability in near-term projections, particularly for regional and smaller-scale trends, but human-induced change becomes more obvious more quickly in projections driven by scenarios with larger and more rapid increases in GHG concentrations.

Global socioeconomic conditions are also projected to continue changing over the next century, but the rate and direction of some change is uncertain. For example, global population is projected to increase to 8.5–10 billion by 2050. Some estimates then show decreases back to about 7 billion during 2050–2100, while others show continued increase to more than 12 billion (UN 2012).

Societal factors are very important determinants of the magnitude of future climate change (because they affect GHG emissions and concentrations). They also help to determine the response to change, and ultimately, the level of effect and vulnerability, because they affect overall wealth, willingness, and ability to allocate resources to address societal issues, including practices and adaptation research. Thorough assessment of the risks and potential effects of climate change on food security thus requires consideration of a range of emissions/concentrations and socioeconomic pathways.